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Modular High Current Test Facility at LLNL

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***Abstract* - This paper describes the 1 MA, 225 kJ test facility in operation at Lawrence Livermore National Laboratory (LLNL). The capacitor bank is constructed from three parallel 1.5 mF modules. The modules are capable of switching simultaneously or sequentially via solid dielectric puncture switches. The bank nominally operates up to 10 kV and reaches peak current with all three cabled modules in approximately 30 µs. Parallel output plates from the bank allow for cable or busbar interfacing to the load. This versatile bank is currently in use for code validation experiments, railgun related activities, switch testing, and diagnostic development.**

I. INTRODUCTION

The 1 MA, 225 kJ test facility was developed as a modular bank adaptable to a multitude of load configurations. Applications include code validation experiments, railgun related activities, switch testing, and diagnostic development. This paper describes the capacitor bank configuration and briefly introduces a few recent applications.

II. CAPACITOR BANK

The bank is composed of three modules each containing two capacitors. Arranged in parallel, two Maxwell 32304 capacitors provide 1.5 mF per module. The three two-capacitor modules are arranged in parallel for total capacitance of 4.5 mF with total peak current operation up to 1 MA. As bank loads vary, care is taken to evaluate voltage reversal for each configuration. For capacitor lifetime considerations, minimization of the reversal is achieved via modifications to the number of load cables and/or the cable lengths.

A. Charging Network

Three 4 kJ/s Lambda A.L.E. 10 kV supplies independently charge the three modules via RG-213 cable. The ability to simultaneously charge the modules to different voltages enhances the pulse-forming capabilities of the bank when the modules are fired sequentially.

After an interlock permissive is given, the hard and soft crowbar relays are lifted. With the charging relay engaged, each supply charges two capacitors (one module) through a pair of paralleled 2 kΩ stackpole isolation resistors. When charge is complete, the supplies are disabled and the charging relays are disengaged. This procedure physically isolates the bank from the power supplies at shot time.

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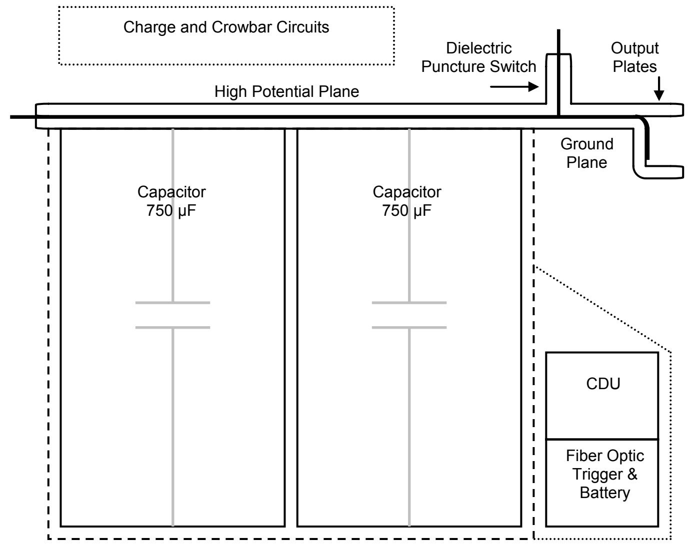

Fig. 1. Single module layout.

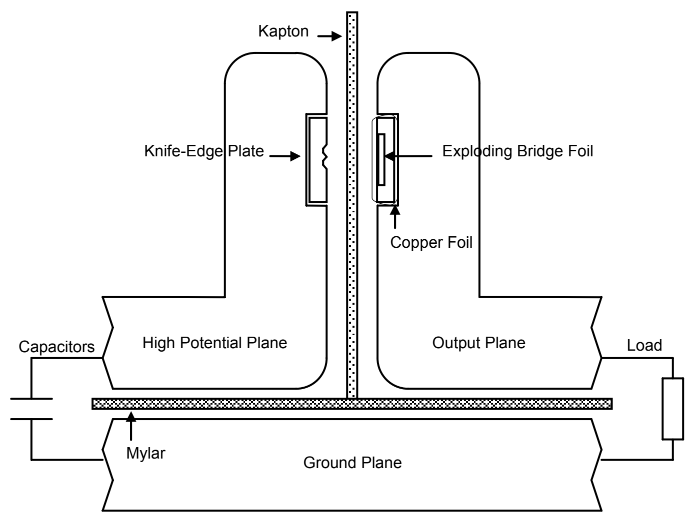

Fig. 2. Detail view of switch assembly [1].

B. Dielectric Puncture Switch

Each module contains a main output dielectric puncture switch. The switch fires as a 5 mil Kapton sheet is punctured by two separate exploding bridge foils (EBFs). The EBFs are housed in a clamped assembly containing 0.25 inch thick stainless steel plates on either side of the switch. The bank-side plate contains a feature for an expendable knife-edge. The output plate contains a 0.125 inch groove for ionized gas venting during the shot. Fig. 1 outlines the layout of a module with the dielectric puncture switch. Fig. 2 shows a detail view of the switch. Previous testing assigned the switch an inductance of approximately 1.5 nH [1].

The EBF is a 0.5 inch wide by 6 inch long shorted parallel plate transmission line. One side of the line is 5 mil copper. The other side of the line is etched 0.175 mil copper. The two fuse elements per EBF are 0.125 inch square constrictions in the etched layer. With the exception of the input current connections, the entire EBF is Kapton laminated. The current connections are connected to 6 ft long RISI type C detonator cables connected to a floating capacitive discharge unit (CDU).

C. Trigger CDU

The main switches are punctured with the discharge from a 6 μF CDU. The CDU floats at shot time and maintains a 5 kV charge via battery power. Electrical isolation is necessary as the CDU is connected to the main high energy storage capacitor bank when the solid dielectric switch is operated. Remote operation enables a 24 VDC battery source to charge the CDU by an internal HV DC/DC converter. At shot time, the CDU is optically triggered with a fiber optic receiver that generates a 34 V, 2 μs wide FWHM tail pulse. The risetime of the fiber optic pulse is roughly 5 ns with jitter of 1 ns. The insertion delay through the CDU is approximately 5 μs and the switch conducts high current about 1 μs after the EBFs explode.

D. Output Connections

The output of the switch is a flat-plate transmission line. The load may be connected to the bank via a continuation of the flat-plate transmission line or through up to 12 Belden YK-198 cables per module. The nominal impedance of the cables is 13.6 Ω with an inductance of 31 nH/ft. The cables have sufficiently handled peak current stresses of greater than 100 kA peak (double the nominal rating) [1]. However, the 6 mm pin multi-lam connectors may begin to show wear above 60-70 kA each.

E. Crowbar Network

After a shot, or in the case of an aborted short, the modules are each equipped to safely discharge through the crowbar network. After the charging supplies are disconnected from the module, the soft crowbar relay drops and dissipates the main capacitor energy into the same two parallel 2 kΩ resistors used for charging isolation. Each resistor is rated to dissipate 159 kJ with a physical length of 16 inches and diameter of 1.625 inches. The peak rated voltage for the resistors is 160 kV. With a full charge, the main capacitors are discharged within seven seconds of the soft crowbar drop.

After eleven seconds from the beginning of crowbar initiation, the hard crowbar and charging relays drop. The hard crowbar provides a direct short across the capacitors and the charging relay shorts the high voltage power supply connections. These actions allow the operator to enter the test cell to complete the safing process.

All crowbar relays are rated at 40 kV. This provides a safety factor of four above the 10 kV operation of the bank. The relays are located in a fail-safe position as they are gravity assisted. The dump status is also easily viewable to the operator upon test cell entry.

F. Diagnostics

The bank is equipped with current and voltage diagnostics to thoroughly characterize its performance. Rogowski coils are located around each capacitor header and module output plate to measure current. Voltage monitors are located on each module and are used to monitor charge and discharge voltages. The voltage monitors provide a 10,000:1 division into plus or minus 1 V input PPM fiber optic transmitters. The fiber optic receivers are located in the screen room. CDU firing timing is also monitored.

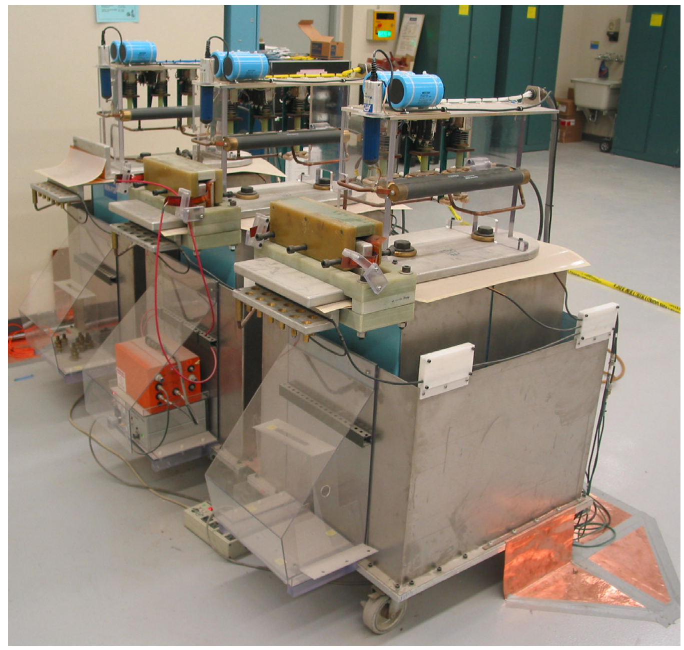

Fig. 3. Photo of the three modules. The middle module is seen equipped with a CDU for the firing of its dielectric puncture switch.

III. EXAMPLE LOADS

Code Validation Experiments

A 35 nH coaxial test fixture was developed to provide high-quality experimental data from a controlled environment undergoing large magnetically-induced deformations. The data is useful for the validation of coupling between LLNL electromagnetic and solid/thermal mechanics codes. A coupled electro-thermal-mechanical simulation self-consistently solves equations of electromagnetics, heat transfer, and non-linear mechanics. Applications include magnetic flux compression generators, electromagnetic launchers, inductive heating and mixing of metals, and micro-electromechanical systems.

The coaxial test fixture was designed to handle a current injection of 1 MA via twelve YK-198 cables. The application of high current levels into the shorted coax applies electromagnetically crushing loads to the aluminum center conductor. The aluminum center conductor test cylinders are of varying wall thicknesses, a nominal 6 inch working length, and a 3 inch nominal diameter. A number of variations are possible, including cylinders with slots or other imperfections.

The fixture is designed such that the cylinders can be instrumented with strain gauges and thermocouples. These diagnostics are connected via Glenair conduit to the signal conditioners and digitzers located within a battery-powered EMI-protected enclosure. When the center conductor is a solid tube (no slots), the strain gauges and thermocouples are located within a Faraday cage and noise-free data may be obtained. The enclosure is connected to the screen room for triggering and post-shot data downloads via fiber optics. The test fixture also allows for Photonic Doppler Velocimetry (PDV) measurements of the radial tube displacements. The probe holders are installed into the outer conductor as seen in Fig. 4. Simulation of a shot is seen in Fig. 5.

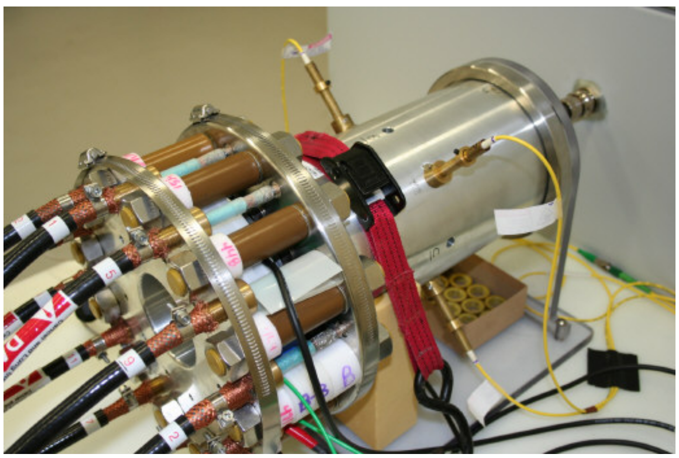

Fig. 4. Coaxial load for code validation experiments. Twelve cables provide the high current feed. PDV probes are located radially on the outer conductor.

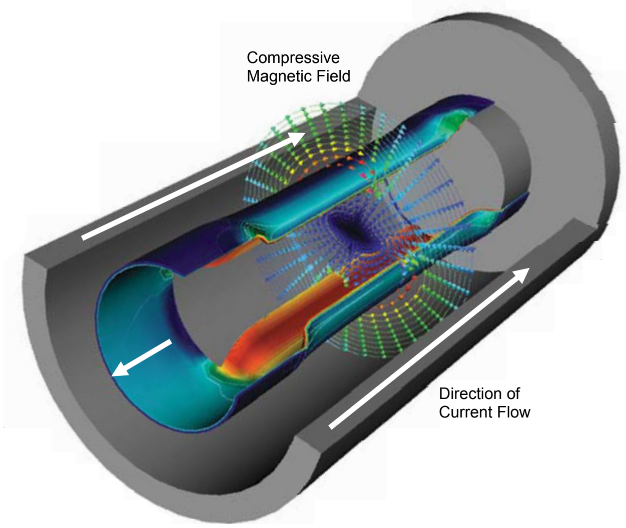

Fig. 5. Simulation of a coaxial load test shot. The slotted center conductor provides a fully three-dimensional problem.

Fixed Hybrid Armature Railgun Studies

A 120 nH fixed hybrid armature test fixture was constructed leveraging legacy hardware from the early 1990s. In this experiment, a railgun with a stationary hybrid armature is coupled to the capacitor bank via twelve YK-198 cables. Two plasma brushes are initiated from exploding aluminum foils. With no gross motion of the armature, the experiment allows for detailed analysis of the plasma behavior including measurements of currents, magnetic fields, plasma pressure, and various optical characteristics (see Fig. 6 and 7).

The experiment permits investigation of armature plasma dynamics due to both ablation and high plasma ejection speeds, as well as steady-state conditions. Diagnostics include a fine array of B-dots for the magnetic field, Rogowski coils for currents, differential voltage probes for brush voltages, and piezo-electric pressure sensors. Fiber optics capture light emission data in preparation for future use of fiber-optic-based pressure sensors and for the development of optical techniques to measure the plasma emission characteristics as a function of time and position. Many of the diagnostics can be seen in experiment setup in Fig. 6.

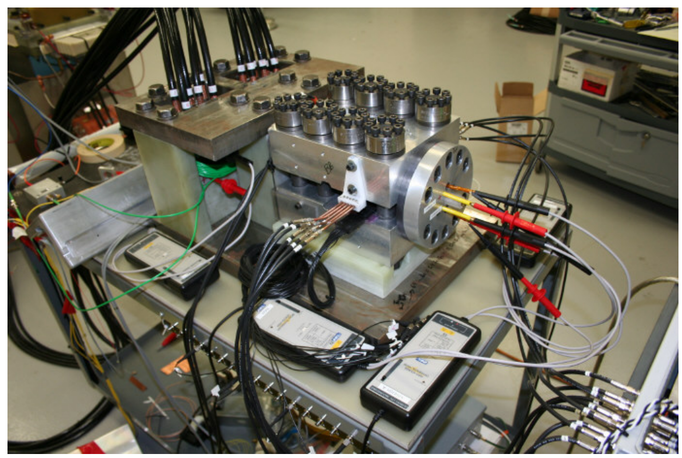

Fig. 6. Fixed hybrid armature experiment hardware with associated diagnostics.

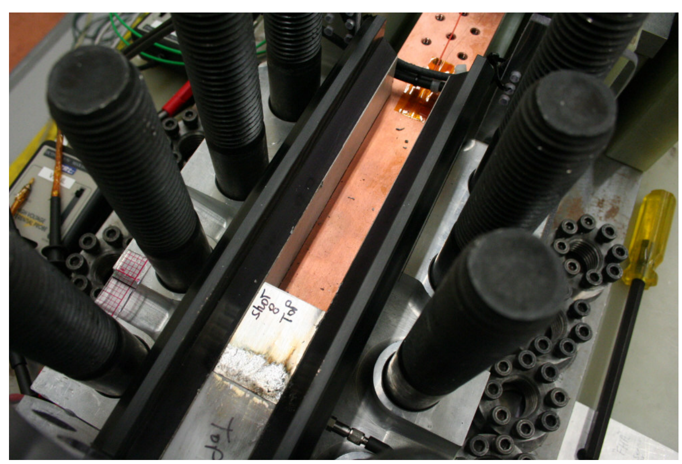

Fig. 7. Top-down view of the stationary armature post-shot mid-disassembly.

Solid-State Switch Testing

Solid-state switching is the future direction for many pulsed power applications with high-current, high-energy capacitor discharge units. LLNL has many switching needs including magnetic flux compression generators, flashlamp banks, pulsed high-field magnets, compact electric power conversion, and electromagnetic launchers.

High current switching poses a unique set of challenges. A recent effort focused on two key switch characteristics: high peak current and high di/dt [2]. High peak current handling decreases the number of parallel switches, thus reducing cost and system complexity. High di/dt capability increases the range of possible loads to the system. Both criteria are important for pulsed power switch selection.

To determine the suitability of light-triggered thyristors for pulsed power applications beyond manufacturers' ratings, devices were stressed beyond the di/dt rating while maintaining low peak currents and, conversely, stressed beyond the peak current rating while maintaining a low current rate of rise.

Solid-state switch testing was conducted in two customizable testbeds. A resistive load was implemented for high di/dt testing while maintaining low peak current (Fig. 8). An inductive load was constructed for high peak current testing while maintaining low di/dt (Fig 9). Each load consisted of a variable number of resistors and inductors, respectively, to target the bounds of operation for the devices. Full pulsewidth was minimized to less than 10% of nominal rating. Switch action was kept orders of magnitude below specified ratings. Switch performance diagnostics included Rogowski coils and current transformers for current measurement and differential voltage probes for voltage drop across the switch. A busbar connection to the bank was utilized to minimize unnecessary circuit inductance. The dielectric puncture switch hardware was shorted and the solid-state devices served at the switch for the bank.

Diagnostic Development

It is often necessary to measure extremely high peak currents when conducting explosive pulsed power experiments. There are a limited number of diagnostics appropriate for accurate measurement of currents at these levels. The most common methods include calibrated inductive field sensors that are susceptible to undesirable field coupling and EMI. Faraday Rotation Diagnostics (FRDs) rely on magneto-optical rather than inductive phenomena and are largely immune to EMI.

FRD sensors have excellent linearity and bandwidth characteristics, and are optically isolated and largely immune to EMI. These qualities make FRDs particularly well-suited for application in experiments that involve large quantities of guided or radiated electromagnetic energy. Since failure modes of FRDs differ from those of conventional inductive field sensors, FRDs offer a level of data redundancy for high-value single-shot experiments that is not easily otherwise achievable. The high current test facility provides a unique environment for this and other diagnostic developments.

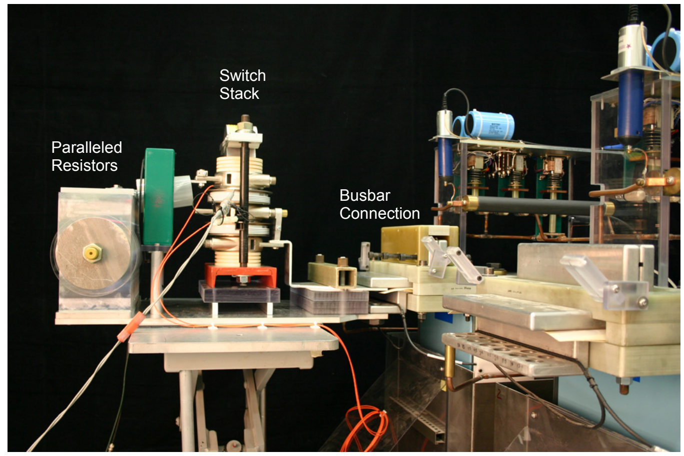

Fig. 8. Resistive load for high current solid-state switch testing.

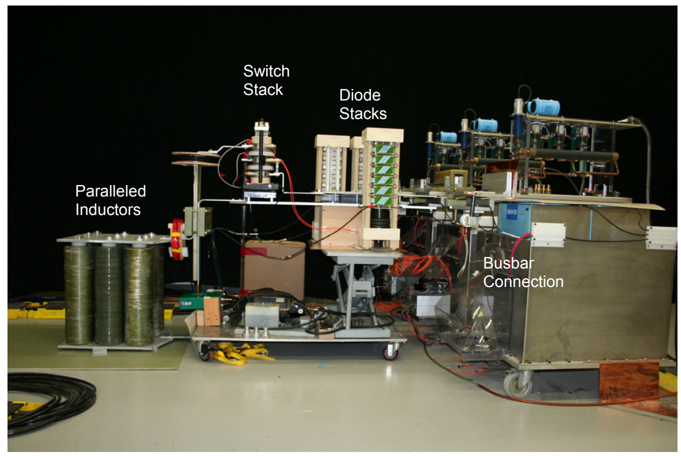

Fig. 9. Inductive load for high di/dt solid-state switch testing.

IV. Summary

A 1 MA, 225 kJ test facility is in operation at LLNL. The capacitor bank is constructed from three parallel 1.5 mF modules. The modules are capable of switching simultaneously or sequentially via solid dielectric puncture switches. The bank operates up to 10 kV and reaches peak current with all three cabled modules in approximately 30 µs. Parallel output plates from the bank allow for cable or busbar interfacing to the load. This versatile bank is currently in use for code validation experiments, railgun related activities, switch testing, and diagnostic development.

References

[1] Richardson, R. A., Cravey, W. R., Goerz, D. A., "Performance of a 10 kV, 625 kA, 85 kJ energy discharge module utilizing a solid dielectric switch", Digest 8th Inter. IEEE Pulsed Power Conf., pp. 187-190, June 1991.

[2] Tully, L. K., Fulkerson, E. S., Goerz, D. A., Speer, R. D., "Evalulation of light-triggered thyristors for pulsed power applications", these proceedings.